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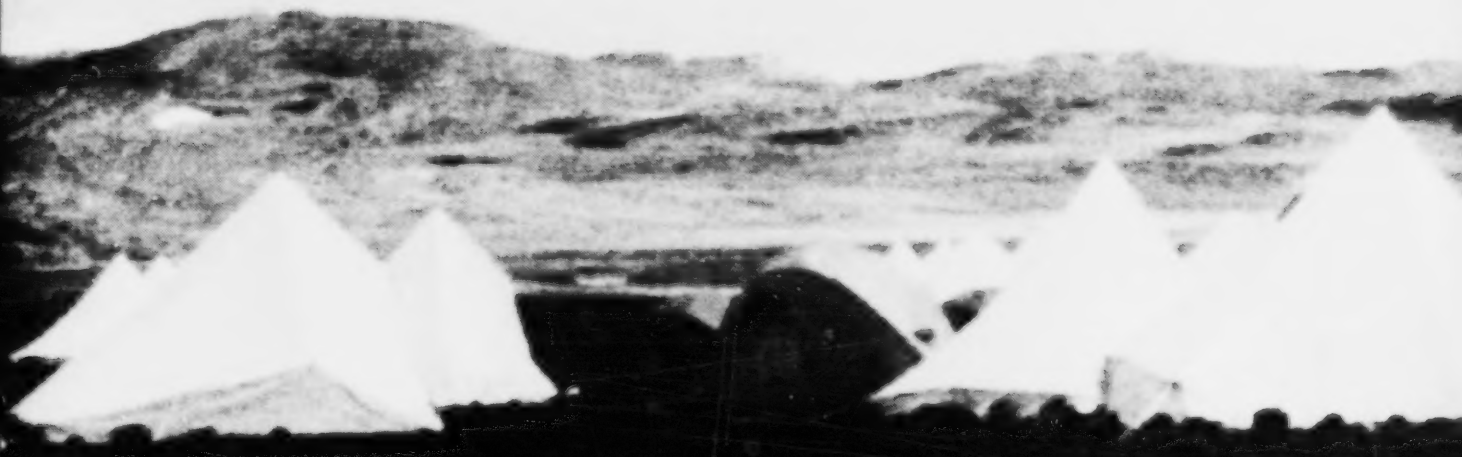
Xueming Yang, David R. Lentz, and Guoxiang Chi

2002



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Petrochemistry of Lake George granodiorite stock and related gold mineralization, York County, New Brunswick[1]

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Yang, X, Lentz, D.R., and Chi, G., 2002: Petrochemistry of Lake George granodiorite stock and related gold mineralization, York County, New Brunswick; Geological Survey of Canada, Current Research, 2002-D7, 10 p.

Abstract: The plagioclase-hornblende-biotite porphyritic granodiorite stock (Au = 32 ppb average) at the Lake George Sb-Au-W-Mo deposit, New Brunswick was sampled (10 samples) from drill core and analyzed. It is metaluminous to weakly peraluminous (A/CNK = 0.99–1.13), calc-alkaline, $Na_2O>K_2O$, and has $(La/Yb)_N$ from 7.34 to 11.14 with a small negative Eu anomaly, as well as obvious negative Nb, Ti, Sr, and Ba anomalies. The Early Devonian ages and volcanic arc affinities (evolved I-type) favour a relationship with the Pokiok Batholith.

Gold-bearing quartz-vein mineralization within the stock and in the proximal metamorphic aureoles highlights its metallogenic association with the intrusion. Silicification, sericitization, and chloritization of the stock associated with quartz-vein mineralization are enriched in Au, As, S, W, Mo, Rb, K, and B. These mineralizing fluids may be derived from the same granodioritic magma crystallizing at depth, although later than the W-Mo mineralization. The gold may be associated with an antimony mineralization episode.

Résumé : Le massif intrusif de granodiorite porphyrique à plagioclase-hornblende-biotite (Au = 32 ppb en moyenne), au gisement de Sb-Au-W-Mo de Lake George (Nouveau-Brunswick), a été échantillonné par prélèvement de carottes de sondage (10), puis analysé. Les résultats des analyses indiquent que ce massif est méta-alumineux à faiblement hyperalumineux (A/CNK = 0,99 à 1,13) et calco-alcalin et qu'il présente des teneurs en Na_2O supérieures à celles en K_2O, un rapport $(La/Yb)_N$ variant de 7,34 à 11,14, une faible anomalie négative en Eu, ainsi que de nettes anomalies négatives en Nb, Ti, Sr et Ba. L'âge du massif, le Dévonien précoce, et les affinités de ses roches avec celles d'un arc volcanique (de type I évolué) tendent à l'apparenter au batholite de Pokiok.

La minéralisation en or dans des filons de quartz à l'intérieur du massif intrusif et dans ses auréoles proximales de métamorphisme souligne l'association métallogénique de celle-ci avec l'intrusion. Les zones de silicification, de séricitisation et de chloritisation associées aux filons de quartz minéralisés dans le massif intrusif sont enrichies en Au, As, S, W, Mo, Rb, K et B. Les fluides minéralisateurs pourraient provenir du même magma granodioritique que celui de l'intrusion dont la cristallisation se déroulait en profondeur, mais ils seraient toutefois ultérieurs à la minéralisation en W-Mo. L'or pourrait être associé à un épisode de minéralisation en Sb.

[1] Contribution to Targeted Geoscience Initiative

INTRODUCTION

The Lake George Sb-Au-W-Mo polymetallic mineral deposit, formerly the largest Sb producer in North America, is located at latitude 67°02′, longitude 45°51′, York County, New Brunswick (Fig. 1). The detailed geology of the deposit was previously investigated (Scratch et al., 1984; Seal et al., 1987; Procyshyn and Morissy, 1990; Caron, 1996). Recently, it has been noted that gold anomalies are widespread in drill cores (Morrissy, 1991a), and ore-grade (up to 0.416 oz/t Au) bodies are locally developed (Morrissy, 1991b). The spatial relationship between Au mineralization and the Lake George granodiorite stock, i.e. Au-bearing quartz-vein mineralization within the stock and in the proximal metamorphic aureoles, suggests that Au mineralization might be related to the intrusion. Elsewhere in the world, gold mineralization in granitic domains has been documented to be mainly related to metaluminous, subalkalic intrusions of intermediate to felsic composition that span the boundary between ilmenite- and magnetite-series, in a continental tectonic setting well inboard of convergent plate boundaries (Lang et al., 2000); however, there are no systematic mineralogical and geochemical studies on the Lake George granodiorite stock available in previous literature, and these data might provide key constraints on whether the petrochemical characteristics of the Lake George granodiorite stock are broadly consistent with this category of gold-associated granite bodies described by Thompson et al. (1999) Lang et al. (2000), and Lang and Baker (2001). To achieve this aim, ten representative granodiorite samples, collected from the diamond-drill holes (DDH) encountering the granodiorite stock at the mineral deposit were analyzed by EMPA, XRF, INAA, and ICP-MS methods for the composition of rock-forming minerals and whole-rock geochemistry including major and selected trace elements. A geochemical comparison of the Lake George granodiorite stock with the Hawkshaw granitic phase of the Pokiok Batholith was made, and a petrogenetic model for the granodiorite stock is briefly discussed. These data provide basic information for analyzing the potential of gold mineralization at Lake George and in similar settings in the Canadian Appalachians.

GEOLOGICAL SETTING OF THE LAKE GEORGE GRANODIORITE STOCK

The Lake George antimony mineral deposit is hosted within deformed Silurian turbiditic metasediments of the Fredericton cover sequence, which comprises massive and bedded greywacke-sandstone, siltstone, and black nongraphic slate (Fyffe and Fricker, 1987). All the metasedimentary units contain varying amounts of matrix carbonate (Procyshyn and Morrissy, 1990). Structurally, the rock units are tightly folded and metamorphosed to lower greenschist facies and cut by a northeast-trending axial-planar spaced cleavage that is related to the Acadian Orogeny (Ruitenberg and McCutcheon, 1982). Chronologically, from oldest to youngest, the polyphase syn- to late-tectonic Pokiok Batholith consists of Hartfield tonalite, Skiff Lake granite, Hawkshaw granite, and Allandale granite (Fig. 1; Ruitenburg and Fyffe, 1982; Lutes, 1987; McLeod et al., 1994). The Hawkshaw granite, a major phase of the batholith, outcrops approximately 3 km northwest of the deposit. It is mainly composed of medium- to coarse-grained, pink K-feldspar, porphyritic, biotite granite to granodiorite with minor equigranular, pink biotite granite (Whalen, 1993).

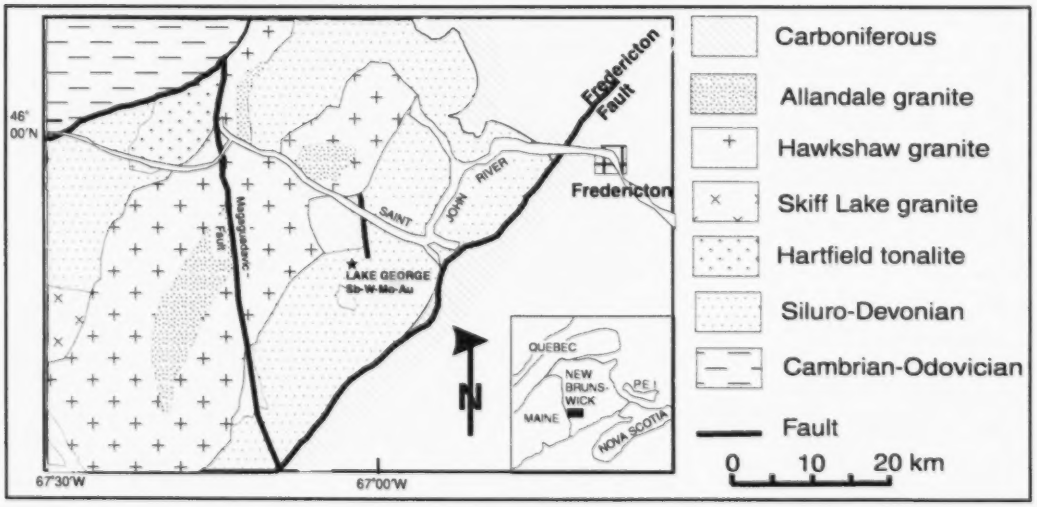

Figure 1. *Geological map of the Lake George and Pokiok area (modified from Procyshyn and Morrissy, 1990; McLeod et al., 1994)*

The Lake George granodiorite stock lacks surface exposure, being completely buried 500 m north of the Hibbard shaft. The intrusion was revealed mainly by exploration drilling to a depth of 435 m (Fig. 2). The stock was intruded into Silurian Kingsclear Group metasedimentary rocks, causing contact metamorphism around the stock, as indicated by the formation of biotite and cordierite in the pelitic rocks (Caron, 1996). Biotite occurs within the entire contact aureole whereas cordierite is restricted to the inner contact halos (Fig. 2; Seal et al., 1987). The fine- to medium-grained porphyritic granodiorite consists of quartz, plagioclase, orthoclase, biotite, trace hornblende, and accessory minerals such as titanite, zircon, apatite, ilmenite, and magnetite. Modal analyses of ten samples, together with CIPW norms, indicate that most samples are granodiorite, as shown in IUGS classification diagram (Fig. 3), the same as the identification by Scratch et al. (1984). The one sample that is classified as monzogranite could be attributed to the K-feldspar alteration. Identical classification results are obtained by utilizing the Ab-An-Or (norms) diagram, so here afterward the samples collected from the stock will be termed as granodiorite, not monzogranite as previously named (Seal et al., 1987). Zircon U-Pb dating for one granodiorite sample gave an age of 412 +5/-4 Ma (M.J. McLeod, pers. comm., 2001), similar to the U-Pb titanite age of the Hawkshaw granite (411 Ma; Whalen, 1993), indicating both of them have an Early Devonian age of crystallization. The Lake George granodiorite also resembles the Hawkshaw granite in major-element chemistry, in that it straddles the plagioclase-biotite tie-line on the ACF diagram

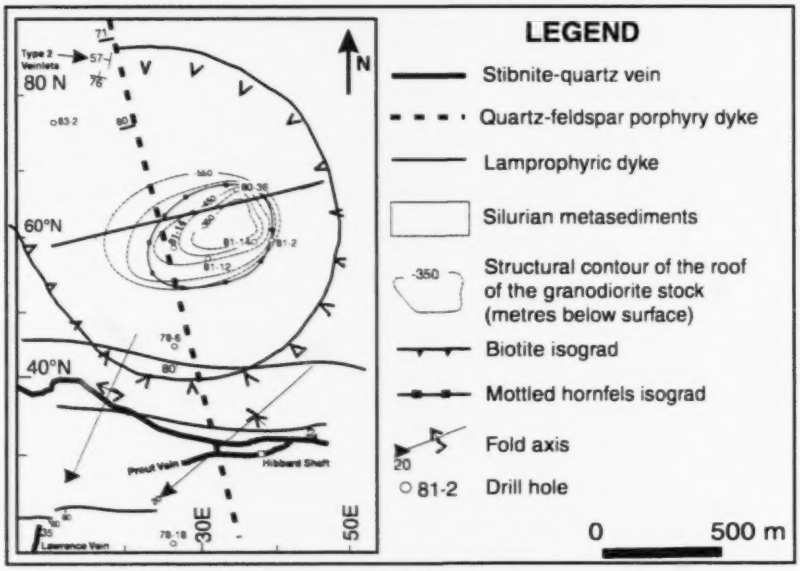

Figure 2.

Schematic geological map of the Lake George mine site (modified from Seal et al., 1987; Procyshyn and Morrissy, 1990). The location of the granodiorite stock is depicted as structural contours of its upper contact (in metres below the surface). Note the concentric disposition of the biotite and mottled hornfels isograds about the stock.

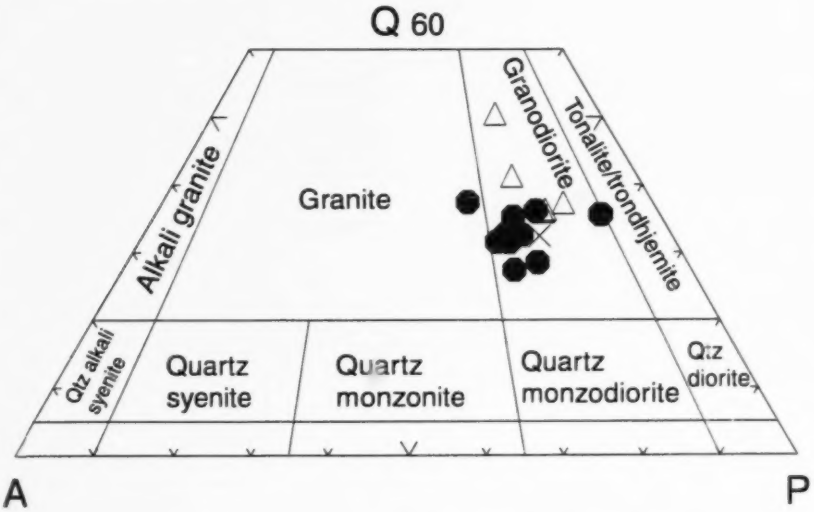

Figure 3.

Quartz (Q)-alkali feldspar (A)-plagioclase (P) mesonormative classification diagram (after Le Maitre et al., 1989) of the Lake George granodiorite. Key: solid circles from this study (Table 1), dashes from Caron (1996), and x from Whalen (1993).

and exhibits low ferric iron ratios indicative of the ilmenite series of granitic rocks that are transitional between I- and S-type granite (Seal et al., 1987).

The Lake George granodiorite stock is cut through by the Hibbard stibnite-quartz veins, the major Sb deposit, and by the quartz-scheelite-molybdenite veinlets (Seal et al., 1987). It is notable that these veins and veinlets have recently been found to contain significant gold contents (up to 0.416 oz/t Au) (Morrissy, 1991a) and locally develop economic Au ore bodies (Morrissy, 1991b). The presence of Au-bearing quartz-vein mineralization within the stock and in the proximal metamorphic aureoles suggests a cogenetic relationship to the stock intrusion. Alteration types within granodiorite associated with Au-bearing quartz-vein mineralization include silicification, sericitization, and chloritization. During alteration, Au, As, S, W, Mo, Rb, K, and B were introduced, demonstrating that mineralizing fluids might be mainly derived from fluids evolving from the same magma crystallizing at depth if we compared the altered granodiorite data of Caron (1996) with unaltered granodiorite data of this study. Relationships between mineralizing veins and veinlets observed in the diamond-drill hole cores and previous investigations (Scratch et al., 1984; Seal et al., 1987) indicate that the timing of Au mineralization is later than the latest stage of granitic magmatism and W-Mo mineralization, but could be the same episode as Sb mineralization.

ANALYTICAL TECHNIQUES

Ten representative granodiorite samples were collected from diamond-drill hole cores at the Lake George mine, each of which consists of an approximately 50 cm to 60 cm long piece of core; any alteration and veining were avoided as much as possible. They were subsampled and crushed with a soft iron shatterbox to pass 200 mesh. Double polished thin sections were made for each of the samples for petrographic observation and electron microprobe analysis (EMPA). Major elements were analyzed on fused glass discs by XRF, and Nb, Zr, and Ga on pressed powder pellets also by XRF at University of Ottawa. The Ag, Cu, Mo, Ni, Pb, Zn, Be, Sr, V, Y, and S were determined by ICP-ES; Ge, Se, In, Sn Te, Tl, Cs, and Bi by ICP-MS; Au, As, Ba, Br, Co, Cr, Hf, Ir, Mo, Ni, Rb, Sc, Ta, Th, U, W, La Ce, Nd, Sm, Eu, Tb, Yb, and Lu by INAA at Activation Laboratories Ltd. A University of New Brunswick internal rock standard RHY94-1 (Lentz, 1995) was analyzed at the same time in order to monitor the quality of analyses. Accuracy and precision for major elements were estimated to be better than 1% relative standard deviation, and all trace elements including rare-earth elements better than 5% relative standard deviation, based on the standard analytical results and precision test.

Electron microprobe analyses were conducted at University of New Brunswick on a JEOL-733 Superprobe with 15 kV accelerating voltage, 10 nA beam current, and a maximum 40 second counting interval. The beam size was set to be 5 μm. A combination of various fused glass, mineral, and metal standards were used with ZAF matrix corrections by means of CITZAF version 3.03. The analytical limits are on the order of 0.05 wt %.

MINERALOGICAL CHARACTERISTICS

Rock-forming minerals in the Lake George granodiorite, including plagioclase, orthoclase, biotite, and hornblende, were analyzed with electron microprobe analysis. Preliminary results are presented herein. The amphibole minerals in the granodiorite mainly belong to calcic hornblendes, which have $\Sigma(Ca+Na)$ in M4≥1.0 with $Na<0.5$, $Si/(Si+Al+Ti)>0.775$, (based on 23 oxygens and normalized to 13 cations), and $Al_2O_3<10$ wt % and $TiO_2<2$ wt %. These hornblende minerals are similar to those reported from I-type granitic rocks elsewhere (White and Chappell, 1983) and are thought to be characteristic of crustal melt-derived amphibole. The Al-in-hornblende barometer (Hammarstrom and Zen, 1986), which was used to estimate the amphibole formation pressure, gave an average lithostatic pressure of 4.7 kbar, equivalent to 15–16 km depth. Stein et al. (2001) have summarized all published post-1986 schemes of Al-in-hornblende barometer, none of which yielded significantly different results. As this lithostatic pressure is too high for the final emplacement depth of this granodiorite stock, it could indicate the pressure at which hornblende crystallized from a magma at depth, prior to final near-surface emplacement (<1 kbar).

Magnesian biotite in the granodiorite has Mg/(Mg+Fe+Mn) ratios greater than 0.5; occupancy of Mg in eight-fold sites greater than 36%; and as well it contains high $Al^{IV}/\Sigma Al$ ratios. These compositions are consistent with the weakly peraluminous composition and higher fO_2 and possibly higher fS_2 crystallization environments for this granodiorite.

The intrusion has a low magnetic susceptibility (4×10^{-5} to 21×10^{-5} SI, average 6×10^{-5} SI) based on measurements on the drill core with the Exploranium KT-9. This indicates a low magnetite content (Ishihara, 1981) consistent with a transition from ilmenite-dominant to magnetite-bearing Lake George intrusion (Seal et al., 1987).

GEOCHEMICAL CHARACTERISTICS

Major elements

Whole-rock major- and trace-element data, including REEs, for the Lake George granodiorite are presented in Table 1. The granodiorite samples have a very narrow compositional range. SiO_2 varies from 65.25 wt % to 68.33 wt %, except for sample LG81-14-1886 that gets a lower total owing to obvious sericitization. All are metaluminous to weakly peraluminous (A/CNK = 0.99–1.13), except for a previously published sample of Caron (1996), which is strongly peraluminous (A/CNK = 1.48, sample no. AR-090-89), possibly due to alteration, although attributed by Caron (1996) to primary processes. All of the granodiorite samples fall in the calc-alkaline AFM field (Kuno, 1968) with relatively high alkali (Na_2O+K_2O) content, ranging from 5.47 wt % to

7.33 wt %, and Na_2O/K_2O ratios of 0.70 to 2.49 (this study), consistent with orogenic granitoid rocks (Maniar and Piccoli, 1989). It is worthy to note that most available data on the granodiorite, which include ten specimens from this study, one sample of Whalen (1993), and five samples of Caron (1996), have Na_2O/K_2O ratio greater than 1, as is typical of I-type granitoid rocks (Chappell and White, 1974; White and Chappell, 1983). In addition, the specimens all have low to intermediate $MgO/FeO_{(T)}$ ratios ranging from 0.32 to 0.41, high TiO_2, and intermediate CaO, P_2O_5, and MgO concentrations (Table 1).

The CIPW norms also indicate compositional homogeneity of the Lake George granodiorite, as the components quartz, orthoclase, albite, and anorthite constitute less than 92% of the norm (DI = 80–92), but higher than 80%, belonging to a typical granitic system. It is interesting that samples

Table 1. Major elements (wt %) and trace elements (ppm, except for Au in ppb) of the Lake George granodiorite stock, New Brunswick.

Samples	LG78-18-1190	LG79-6-612	LG80-36-1647	LG81-2-1741	LG81-12-1567	LG81-14-1291	LG81-14-1886	LG81-19-1351	LG83-2-1995	LG83-2-2461
SiO_2	65.71	67.27	67.11	67.85	67.09	66.33	62.39	65.25	68.25	68.33
TiO_2	0.60	0.49	0.55	0.54	0.58	0.57	0.59	0.57	0.52	0.50
Al_2O_3	14.83	14.23	14.86	14.11	14.69	13.91	14.56	15.24	14.72	14.39
Fe_2O_3	3.78	3.24	3.26	3.13	3.38	3.24	3.36	3.24	2.94	3.07
MnO	0.07	0.05	0.07	0.06	0.07	0.06	0.07	0.06	0.06	0.06
MgO	1.53	1.14	1.16	1.09	1.21	1.17	1.26	1.12	1.00	0.98
CaO	3.35	2.05	2.58	2.60	2.89	3.10	3.01	2.99	2.72	2.66
Na_2O	3.90	2.77	3.32	3.33	3.42	3.19	3.48	3.52	3.53	3.42
K_2O	1.57	3.98	3.90	3.27	3.36	2.76	3.23	3.85	3.66	3.63
P_2O_5	0.14	0.14	0.13	0.13	0.14	0.14	0.13	0.13	0.12	0.12
SO_2	1.11	0.71	0.27	0.08	0.40	0.61	0.23	0.04	0.15	0.09
L.O.I.	4.40	3.00	1.60	2.50	2.00	3.90	2.1	1.5	1.30	1.20
Total	101.0	99.1	98.8	98.7	99.2	99.0	92.3	96.0	99.0	98.5
Rb	68	139	154	142	119	112	159	136	158	187
Cs	6	6	8	6	8	7	9	6	10	10
Ba	260	580	650	490	310	360	480	710	360	450
Sr	317	177	276	288	232	223	300	310	267	244
Ga	16	16	16	16	16	16	15	16	16	16
Tl	0.3	1.0	0.8	0.6	0.5	0.5	0.9	0.5	1.1	0.9
Ta	<0.5	<0.5	1.8	2.5	1.8	1.6	<0.5	1.5	1.6	1.6
Nb	12.5	15.5	14.5	14.3	14.5	13.3	12.6	14.1	14.9	14
Hf	5	6	5	5	4	4	4	5	5	5
Zr	174	179	166	168	173	167	160	194	179	181
Y	20	22	23	19	16	13	19	28	22	18
Th	12.2	14.9	15.5	12.8	14.4	13.2	14.1	13.8	14.7	14.5
U	6.4	9.2	6.8	6.3	8.4	5.8	6.6	7.1	6.2	8.2
La	29.5	30.1	37.0	31.5	29.4	31.4	30.4	32.5	30.0	27.2
Ce	50	51	62	50	49	52	51	52	49	46
Nd	12	8	16	14	15	15	13	19	15	10
Sm	3.9	4.1	4.9	4.2	4	4.1	3.9	4.4	4.3	4.2
Eu	1	1.1	1.2	1	1.1	1	1.1	1.2	1	1.1
Tb	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	0.8	<0.5
Yb	1.9	2.3	2.6	2.2	2.2	1.9	1.9	2.1	2.4	2.5
Lu	0.28	0.36	0.38	0.32	0.34	0.29	0.29	0.31	0.36	0.39
Cr	30	10	15	16	10	21	12	13	11	13
Ni	17	5	7	7	6	11	6	6	7	5
Co	10	8	9	8	8	9	7	9	7	8
Sc	9.2	7.9	8.1	8.8	7.4	7.9	8.2	7.8	7	7.9
V	60	49	52	55	51	59	59	53	50	48
Cu	14	56	24	9	72	140	41	8	21	23
Pb	27	25	17	15	18	23	18	21	27	30
Zn	59	38	48	50	42	39	51	47	48	45
Mn	623	430	590	584	482	506	628	541	579	548
Bi	1.7	3.8	11.9	10.5	0.4	0.8	0.2	0.2	16.3	1.4
Cd	<0.3	<0.3	<0.3	<0.3	<0.3	<0.3	<0.3	<0.3	<0.3	<0.3
Sn	<1	<1	<1	<1	<1	1	<1	<1	<1	<1
W	<1	4	6	8	31	<1	5	<1	<1	1
Mo	2	1	7	3	4	6	2	6	6	33
Be	3	5	4	4	4	4	4	4	4	4
Au	<2	16	75	33	<2	2	8	<2	77	10
Ag	0.6	0.4	0.4	0.5	0.5	0.4	0.5	0.4	0.4	0.4
Ge	<0.1	0.3	0.2	0.2	<0.1	<0.1	<0.1	0.3	0.4	0.2
As	31.9	28.2	5.6	2.9	4	365	13.5	4.9	3.5	4.5
Se	0.6	0.6	0.5	0.3	0.7	0.8	0.4	0.4	0.5	0.3
Sb	4.5	27.9	6	4.3	2.6	6.5	5.6	4.8	1.2	1.2

contain 2.44–3.81% hypersthene and corundum in the norms. According to the Q-Ab-Or-H_2O phase equilibrium diagram, the bulk composition of the intrusion corresponds to an intermediate equilibrium emplacement depth of about 2.0 kbar; this is not the final emplacement depth, which based on texture is on the order of 1 kbar. The fluorine concentration (Whalen, 1993) in the granodiorite is not high enough to affect the eutectic of this system.

Trace elements

The primitive-mantle normalized trace element spider diagram for the Lake George granodiorite (Fig. 4A), shows an obviously negative Nb anomaly, features considered indicative of subduction-related plutonism (Thompson et al., 1984) and typical of crustal-derived granite. Titanium, barium, and strontium also exhibit negative anomalies, which suggest that feldspar and Ti-rich phrases might be involved in the melt-crystal equilibrium. Low abundances of Zr (160–193 ppm), Zn (39–59 ppm), and Ga (15–16 ppm) indicate that the granodiorite samples fall into the field of I-type granitoid rocks, which is corroborated by the geochemical discrimination plots of Whalen et al. (1987) on which samples fall in the field of orogenic granitoid rocks. Based on comparison with the average analyses of I-, S-, and A-type granitic rocks from the Lachlan Fold belt, Australia (White and Chappell, 1983), the average trace-element abundance of the Lake George granodiorite is very similar to the I-type granite average in its low large-ion-lithophile element (LILE) contents, e.g. Rb (137 ppm), Sr (263 ppm), and Ba (465 ppm) and low high-field-strength elements (HFSE) contents, e.g. Nb (14 ppm), Zr (174 ppm), Th (14 ppm), U (7 ppm), and Y (20 ppm). The transition elements are low to moderate for granitoid rocks, e.g. V (54 ppm), Cr (15 ppm), Co (8 ppm), Ni (8 ppm), Cu (41 ppm), and Zn (46 ppm). Chondrite-normalized REE patterns for the Lake George granodiorite rocks (Fig. 4B) are all moderately fractionated and have LREE enrichment $(La/Yb)_N$ ranging from 7.34 to 11.14, with small negative Eu anomaly (Eu/Eu* = 0.66–0.80), and no Ce anomaly. These REE patterns are typical of arc-like, I-type granitoid rocks (Whalen et al., 1987), with significant amphibole fractionation.

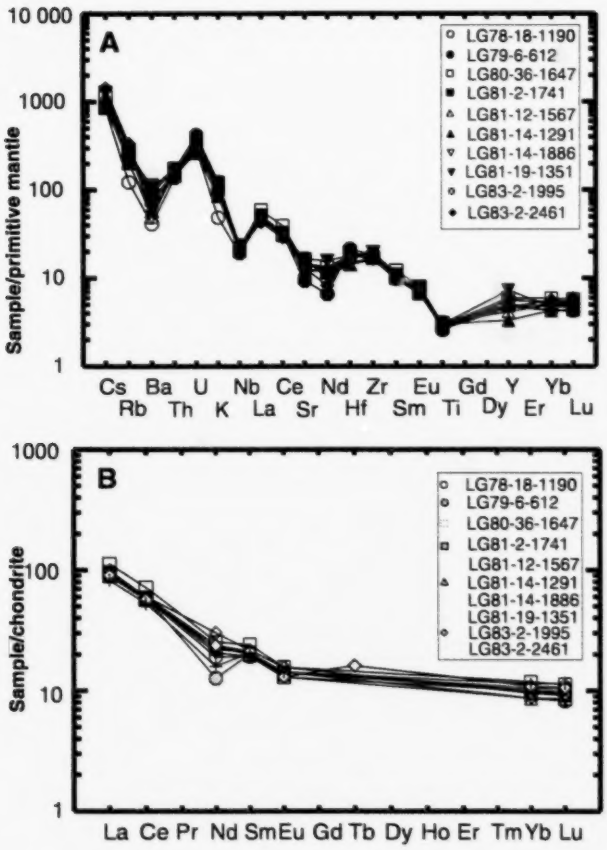

***Figure 4. A)** Primitive-mantle normalized trace element spider diagram for the Lake George granodiorite. The primitive mantle values are from Taylor and McLennan (1985). **B)** Chondrite-normalized (CN) rare-earth-element patterns for the Lake George granodiorite. The CN-normalizing values are from Sun (1982).*

The mineralizing elements in the granodiorite have variable Au (< 2 ppb to 75 ppb; average 32 ppb), Mo (1– 33 ppm; average 7 ppm), W (<1 ppm to 31 ppm; average 9 ppm), Bi (0.2–16.3 ppm; average 4.7 ppm), and Sb (1–28 ppm; average 6 ppm); these values are well above crustal averages for Au (2.5 ppb), Mo (1.1 ppm), W (1.0 ppm), Bi (0.085 ppm), and Sb (0.3 ppm) (Wedepohl, 1995), indicative of relative fertility.

TECTONOMAGMATIC CHARACTERISTICS

The geochemistry of igneous rocks bear a close relationship to their tectonic settings of formation. On the basis of major elements and mineralogy, Maniar and Piccoli (1989) categorized granitoid rocks into seven types by tectonic settings: 1) island-arc granitoid rocks (IAG), 2) continental-arc granitoid rocks (CAG), 3) continental collision granitoid rocks (CCG), 4) postorogenic granitoid rocks (POG), 5) rift-related granitoid rocks (RRG), 6) continental epeirogenic uplift granitoid rocks (CEUG), and 7) oceanic plagiogranitic rocks (OP). Of these, the island-arc granitoid, continental-arc granitoid, continental collision granitoid, and postorogenic granitoid are considered orogenic granitoid rocks, and the rift-related granitoid, continental epeirogenic uplift granitoid, and oceanic plagiogranitic rocks are considered anorogenic granitoid rocks. Following the procedures of their discrimination, the Lake George granodiorite samples plotted in the fields of island-arc granitoid+continental-arc granitoid+continental collision granitoid and postorogenic granitoid (not shown), indicating that they represent orogenic granitoid rocks. Based on the Shand's index criteria set by Maniar and Piccoli (1989), the granodiorite could not be continental collision granitoid, owing to the index in the most samples being less than 1.15; however, it is impossible to distinguish between island-arc granitoid and continental-arc granitoid with the scheme

established by these researchers because too many variables control granite chemistry besides tectonic setting. In order to test the results obtained above, we also used the R1-R2 discrimination diagram by Batchelor et al. (1985)(not shown) to examine the tectonic setting of the Lake George granite. Most samples cluster in the field of 'pre-plate collision setting', which is thought to be equivalent to that of island-arc granitoid and/or continental collision granitoid.

Pearce et al. (1984) classified granite into four main groups: ocean ridge (ORG), volcanic arc (VAG), within plate (WPG), and syncollision granitic rocks (COLG), according to their tectonic environments with the help of trace elements such as Y, Yb, Nb, Ta, and Rb. The Lake George granodiorite data cluster in the volcanic-arc granitoid field (Fig. 5A, B; Pearce et al., 1984) using Nb-Y-Rb (and Ta-Yb) systematics, although three samples from Caron (1996) plotted along the boundary with the syncollisional (S-type) and within-plate (A-type). On the Rb-Hf-Ta diagram (Harris et al., 1986)(not shown), the Lake George granodiorite data fall between volcanic arc and late- to postcollisional granitoid fields, indicative of an evolved I-type magmatic system. No foliation has been observed in this granodiorite, consistent with a late tectonic age of emplacement. The U-Pb zircon dates for the granodiorite indicates the stock was emplaced at the Early Devonian, at the late stage of Acadian Orogeny (Ruitenberg et al., 1982).

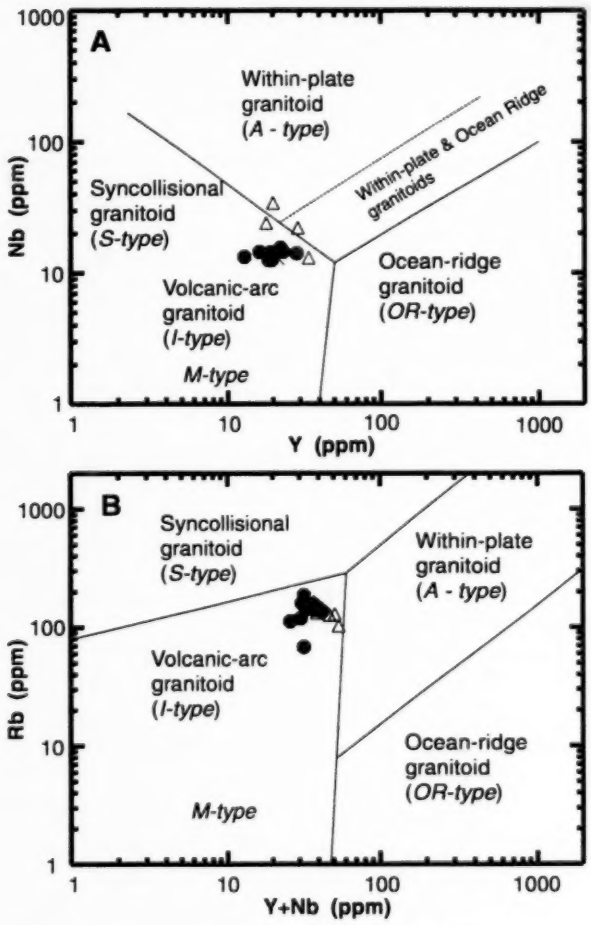

Figure 5. *Tectonomagmatic discrimination diagrams for the Lake George granodiorite (after Pearce et al. (1984) and modified by Christiansen and Keith (1996)). **A)** Y versus Nb; **B)** (Y+Nb) versus Rb. Key: solid circles from this study (Table 1), dashes from Caron (1996), and x from Whalen (1993).*

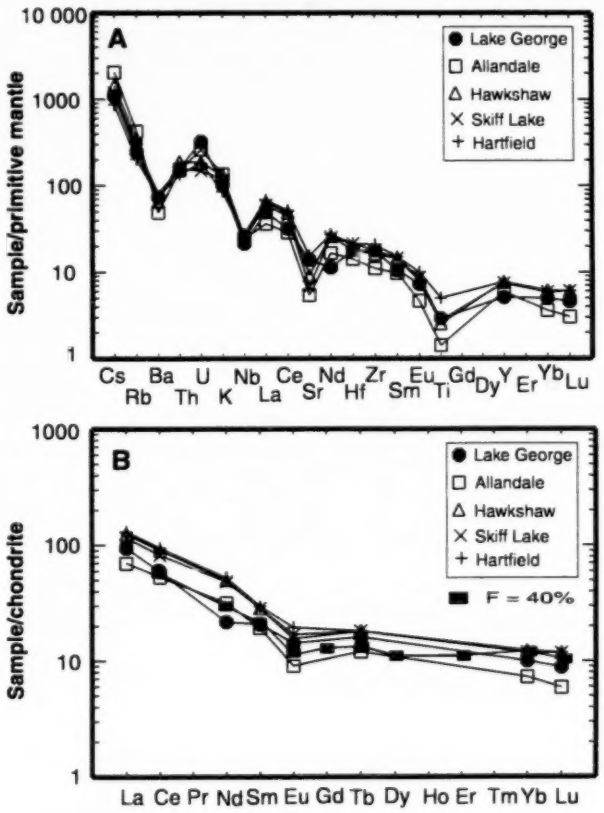

Figure 6. *Comparison of the Lake George granodiorite (solid circle) with different phases of granitic rocks from the Pokiok Batholith (see Table 2). The geochemical data of the Pokiok Batholith are from Whalen (1993). **A)** primitive mantle-normalized, trace-element spider diagram. The primitive mantle values are from Taylor and McLennan (1985). **B)** Chondrite-normalized (CN) rare-earth-element diagram for the Lake George granodiorite, the Pokiok Batholith and the calculated melts (solid square) from 40% partial melting of the lower continental crust (Taylor and McLennan, 1985), leaving a granulite residue (clinopyroxene 46%, plagioclase 15%, orthoclase 7%, quartz 25%, hornblende 7%). The CN-normalizing values are from Sun (1982).*

BRIEF COMPARISON OF THE LAKE GEORGE GRANITE STOCK TO THE POKIOK GRANITE BATHOLITH

Comparison of our data with the database of Whalen (1993) for the Pokiok Batholith, located 3 km northwest of the Lake George, indicates that there are similarities both in major and trace elements between the stock and the Hawkshaw phase of the batholith (Table 2). These geochemical affinities and zircon U-Pb dating favour an interpretation of the Lake George granodiorite stock as a cupola of the Hawkshaw granite. This is consistent with the shallow dip of the southern contact of the Pokiok Batholith based on gravity profiles (Thomas and Willis, 1989). A few hornblende grains in the Lake George granodiorite suggest, however, that it is a less fractionated than the main phase of the Hawkshaw granite, which contains no amphibole. Based on the spider diagram and REE patterns (Fig. 6A, B), the granodiorite could be derived from the Pokiok Batholith by differentiation, probably via fractional crystallization (hornblende, plagioclase, ±magnetite) from the Hawkshaw granite.

Table 2. Geochemical comparison of the various different phases of the Pokiok Batholith, New Brunswick (Whalen, 1993)

Number of samples	Allandale		Hawkshaw		Skiff Lake		Hartfield		Lake George	
	4		14		17		4		10	
	AVE	STDEV	AVE	STDEV	AVE	STDEV	AVE	STDEV	AVE	STDEV
SiO_2	71.58	0.29	69.07	1.62	68.90	2.88	62.13	4.28	66.56	1.69
TiO_2	0.27	0.04	0.48	0.10	0.52	0.25	0.95	0.36	0.55	0.04
Al_2O_3	14.45	0.06	14.75	0.40	14.93	0.93	16.08	0.60	14.55	0.38
Fe_2O_3	0.50	0.13	0.96	0.19	0.76	0.16	1.35	0.44	3.26	0.21
FeO	1.09	0.28	1.63	0.43	2.39	1.41	3.60	1.25	na	
MnO	0.06	0.01	0.07	0.01	0.08	0.02	0.09	0.02	0.06	0.01
MgO	0.52	0.10	0.98	0.25	1.12	0.51	2.39	0.96	1.17	0.15
CaO	1.34	0.43	2.18	0.32	2.07	0.89	4.41	0.88	2.79	0.34
Na_2O	3.78	0.17	3.73	0.10	3.43	0.60	3.67	0.29	3.39	0.27
K_2O	4.36	0.59	4.26	0.21	3.82	0.62	2.78	0.47	3.32	0.68
P_2O_5	0.18	0.06	0.18	0.04	0.18	0.06	0.23	0.08	0.13	0.01
LOI	0.96	0.16	0.77	0.20	0.85	0.28	0.95	0.16	2.49	1.12
Total	99.3		99.3		99.2		98.8		98.2	
Rb	235	61	193	16	162	44	113	23	137	31
Cs	14.4	6.7	10.0	2.8	8.3	4.6	6.1	1.9	7.6	1.6
Ba	310	45	414	73	511	244	470	30	465	140
Sr	103	31	175	23	129	52	292	53	263	42
Ga	17	1	19	1	18	2	21	2	16	0
Tl	<1	<1	2	1	2	1	<1	<1	0.7	0.2
Ta	2.10	0.50	1.80	0.32	1.45	0.64	1.53	0.25	1.77	0.31
Nb	16	3	17	1	16	2	18	3	14	1
Hf	4	1	5	1	6	3	6	1	5	1
Zr	108	21	159	37	175	82	204	42	174	9
Y	23	2	30	6	29	7	30	5	20	4
Th	13.3	3.1	16.7	4.2	13.7	3.0	11.9	3.7	14.0	1.0
U	5.8	5.4	4.1	1.2	3.3	1.5	4.0	1.3	7.1	1.1
La	23	4	41	11	38	14	43	7	31	2
Ce	46	6	78	20	71	27	82	8	51	4
Nd	20.0	2.4	31.6	7.6	30.6	12.2	32.9	3.5	13.7	3.0
Sm	3.9	0.4	5.8	1.3	5.8	2.3	6.0	0.8	4.2	0.3
Eu	0.7	0.2	1.2	0.2	1.3	0.6	1.5	0.3	1.1	0.1
Tb	0.6	0.1	0.9	0.2	0.9	0.3	0.9	0.2	0.8	0.0
Yb	1.6	0.1	2.7	0.8	2.6	0.7	2.6	0.3	2.2	0.2
Lu	0.2	0.0	0.4	0.1	0.4	0.1	0.4	0.0	0.3	0.0
Cr	10	6	12	5	20	17	32	13	15	6
Ni	3	1	5	2	10	7	11	6	8	4
Co	7	6	6	1	8	4	14	6	8	1
Sc	5.3	0.4	8.2	1.8	9.7	3.4	14.7	4.9	8.0	0.6
V	22	5	45	12	59	32	108	46	54	4
Cu	4	3	7	2	20	13	17	8	41	38
Pb	21	5	22	3	20	3	15	5	22	5
Zn	38	3	46	9	52	17	69	20	47	6
Bi	1	0	0	0	0	0	0	0	4.7	5.6
Sn	7	4	6	5	4	2	3	1	1	0
W	3	3	1	1	1		1	0	9	10
Mo	2	1	<1		1		2	0	7	9
Be	6	1	5	1	5	1	5	1	4	0
Au	1	0	2	2	1	1	2	1	32	29
Ge	5	0	7	3	8	4	5	0	0.2	0.1
As	0.9	0.5	1.6	0.8	1.8	1.2	1.2	0.3	46.4	106.7
Se	1	1	2	1	2	1	2	0	1	0
Sb	0.3	0.2	0.4	0.2	0.4	0.2	0.3	0.1	6.5	7.4

PETROGENETIC MODELLING FOR THE GRANODIORITE STOCK

Geochemical and mineralogical data from the Lake George granodiorite provide constraints on its source and point to derivative from igneous materials derived from the mantle. Mixing between a mantle-derived basic magma and an upper crust-derived acid melt does not appear to be a viable option as there is no gabbro intrusion nearby and no mafic igneous inclusions were identified. Only a few greywacke and slate xenoliths exist in these intrusions, indicating only local country rock interaction. It is possible that carbonaceous host-rock assimilation could have resulted in high-level magmatic reduction processes that produced ilmenite locally in the Lake George granodiorite (Seal et al., 1987).

Rare-earth element numerical modelling was used to test the feasibility of producing a melt similar in composition to the Lake George granodiorite from a lower crustal source, similar in composition to infracrustal continental crust, at a metamorphic grade not less than amphibolite facies. Since there are striking similarities in the spider diagram and REE patterns between the granodiorite and the Hawkshaw granite (Fig. 6A, B), the former might be a derivative of the latter. The accessory minerals with large REE partitioning coefficients, such as titanite, zircon, and apatite, could not be part of the fractionating or residual minerals, hence, REE melt-residue distribution equilibria might be modelled with rock-forming minerals.

The concentration of a trace element in the melt C_l can be related to its concentration in the unmelted initial source C_o by the following equation (Hanson, 1978).

$$C_l/C_o = 1/[D_{RS}+F(1-D_{RS})] \quad (1)$$

where D_{RS} is the bulk partition coefficient of the residual solid and F is the weight fraction of melt produced. D_{RS} is related to the residual mineralogy by the expression.

$$D_{RS} = X_1 kd_1 + X_2 kd_2 + X_3 kd_3 + \ldots \quad (2)$$

Where X_1 and kd_1 are the percentage proportion of mineral 1 in the residual solid and Nersnt partitioning coefficient for the element in mineral 1, respectively; the meanings of X_2 and kd_2 are the same as those of X_1 and kd_1, and so forth. Rare-earth element mineral-melt partition coefficient data compiled for the granitic compositions by Rollinson (1993) were used for model calculations.

By using values of average granodiorite for C_l and the lower continental crustal estimate of Taylor et al. (1985) for C_o, the residual mineral weight percentage proportion X for n number of minerals and the degree of partial melting, F, were calculated in the manner as described by Minster and Allègre (1978). The results show that the granodiorite stock could be derived from 30–40% partial melting of the lower crust, probably at amphibolite facies, leaving a granulite residual containing the mineral assemblage: hornblende+clinopyroxene+plagioclase+orthoclase+quartz (Fig. 6B).

CONCLUSIONS

The Early Devonian Lake George granodiorite stock exhibits petrochemical features typical of an I-type intrusion, derived from partial melt of arc-like lower continental crust in a volcanic arc to late orogenic environment, at the same time as the adjacent polyphase Pokiok Batholith. It most closely resembles the Hawkshaw phase of the batholith, even though it has mineralogical differences implying a petrogenetic association linked by fractional crystallization.

Gold-bearing quartz-vein mineralization within the granodiorite stock and in proximal metamorphic aureoles highlights a cogenetic association. Our petrochemical data suggest that the Lake George granodiorite stock is broadly comparable to those considered to be favourable for intrusion-related gold system (Lang et al., 2000). First, it is metaluminous, subalkalic, and has an intermediate composition. Second, it shows typical I-type characteristics, and the abundance of ilmenite indicate a relatively reduced nature of the magma. Thirdly, the anomalous concentrations of Au in the granodiorite, in addition to Sb, Mo, W, suggest that the magma was enriched in these elements, thus having a relatively high potential of producing auriferous fluids.

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